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Procedia Engineering 32 (2012) 621 – 627

Procedia Engineering

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I-SEEC2011

A comparative study of replicated pure Al and AC3A composite foams

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Elsevier use only: Received 30 September 2011; Revised 10 November 2011; Accepted 25 November 2011.

Abstract

Pure Al and AC3A Al alloy, mixed with SiC particles, have been used to produce open-cell composite foams through replication process of polyurethane foam preform, assisted with infiltration pressure. The addition of SiC particles is between 1 – 5 wt.%. A comparative examination of cellular microstructure and compressive strength of both foams is undertaken. It is demonstrated that although both have similar foam structure and particle content, but the disparities in matrix microstructure and properties result in distinct mechanical properties.

Keywords: aluminium foam; investment casting; metal-matrix composite; porosity

1. Introduction

Metallic foams are a new class of engineering materials which have excellent combined properties such as low density, high specific strength, large energy absorption capacity and high service temperature [1, 2]. They can be classified into two types; open-cell and closed-cell foams, according to their pore structures. The pores of open-cell foams are interconnected and fluid can pass through, while those of the closed-cell foam are not interconnected. Due to the open-pore structure and large internal surface area, open-cell foams are preferential for functional applications, such as filters, sound insulators and heat exchanger [3, 4]. In many cases, the use of open-cell foams is only in low stress applications [5, 6, 7].

There are many methods to produce open-cell foams. Replication process is one of popular foam-making techniques. This method can produce a net-shape material by making hollow space from preform

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doi:10.1016/j.proeng.2012.01.1318

and fill it with molten metal. It is similar to investment casting method, commonly used in jewelry industry. This process is used in Al foam production for uniform pores and foam structures [7, 8].

Among various types of metallic foams, aluminium (Al) is the most widely used base metal. It has many advantages, such as cheap price, low density, low melting temperature and good corrosion resistance. AC3A is a pressure die-casting Al alloy of the Japanese trademarks. It contains high silicon (Si) content close to the eutectic point in the Al-Si binary phase diagram. The alloy possesses high corrosion resistance and excellent castability, making it suitable for complex casting where intricate sections are required. The alloy also has better mechanical properties than conventional Al.

To improve mechanical properties and wear resistance, fine ceramic particles are often introduced into the base Al to construct metal matrix composite structure. Silicon carbide (SiC) is a high hardness ceramic material that is a suitable reinforcement for Al. Addition of particulated SiC results in an improvement in strength and hardness of Al and Al-alloy matrix composites.

The present work aims to study the comparison between replicated pure Al and AC3A matrix composite foams. Examination in structure and mechanical properties of different types of composite foams is performed. The effect of SiC addition to mechanical properties in two types of foams is also investigated.

2. Experimental procedure

Open-cell reticulated Al composite foam samples were produced using open-cell polyurethane (PU) foam (Sydney Heath & Son), with the pore size of 8 ppi, to create a cellular pattern. The two pieces of 50×25×90 mm PU foams were invested with Paris plaster into a cylindrical mold of 120 mm diameter, followed by sintering in a resistant furnace at 650°C for 8 h, in order to strengthen the mold and remove the PU foams. To prepare a composite sample, pure Al ingot with 99.7% purity was sectioned and melted in an alumina crucible at 750°C for 60 min and added with SiC particles of various amounts between 1 and 5 wt.%. The composite mixture was stirred using modified-cooking stirrer for 5 min before cooling of the crucible in water. Composite samples of AC3A Al alloy with SiC particles were fabricated with the same method as pure Al. To fabricate composite foams, pure Al and AC3A Al alloy mixtures were remelted at 1000°C for 10 min and infiltrated into the plaster mold with a nitrogen gas pressure of 100 psi, using Old Moon BU 450 vacuum system casting machine. After infiltration process, the composite foams were obtained after rupturing the plaster mold by quenching in water for few minutes. The foam samples were thoroughly cleaned using a water jet system.

Characterization of composite foams was prepared by sectioning the samples into a rectangular rod with the dimension of 10×10×10 mm, using a precision cutting machine (Struers Accutom-5). Standard grinding and polishing of Al samples were performed with etching in sodium hydroxide solution and 65% nitric acid. Macro- and microstructure of samples were examined with the aid of a JSM-6400 JEOL scanning electron microscope (SEM).

A universal testing machine (Shimadzu EZ-S) with 50 N load cell was used for mechanical testing in order to determine compressive characteristic and yield strength. The minimum dimension of compressive foam samples should be at least seven times of cell size. Testing samples were sectioned into rectangular rods with 20×20×20 mm dimension. A constant cross-head speed of 1 mm/min was used for all tests.

3. Results and discussion

Fig. 1 presents the morphology of SiC particles. The particles have angular shape and smooth surface, with a mean diameter of 5.38 μm and D_{10}, D_{50} and D_{90} of 0.06, 0.1 and 19.78 μm, respectively. The analysis of particle size distribution suggests that most particles are not larger than 20 μm and more than 50% of particles are smaller than the mean value. The particles are well distributed and no agglomeration of particles is found.

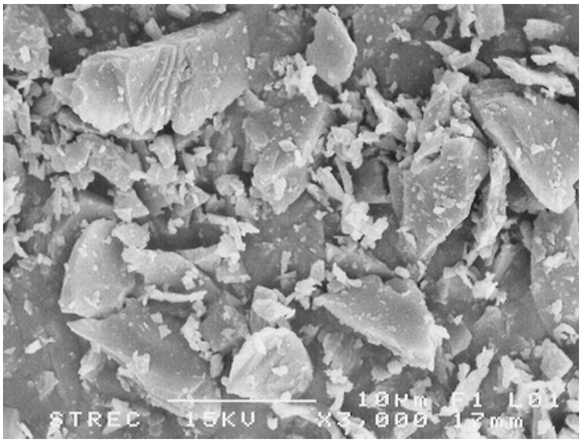

Fig. 1. The morphology of SiC particles

Table 1 presents the chemical composition of AC3A. In this alloy, Si is the main alloying element, up to approximately 20 wt.%. Higher Si content results in higher strength and elastic modulus, but causes a decrease in ductility in Al alloy.

Table 1. The chemical composition of AC3A alloy

Alloy	wt.%										
	Mg	Cu	Si	Zn	Fe	Mn	Ni	Ti	Pb	Sn	Cr
AC3A	0.015	0.015	12	0.015	0.2	0.015	0.02	0.01	0.015	0.015	0.02

Fig. 2 shows the comparative macro-structural figures of Al and AC3A composite foams. In all cases, both composite foams have similar structure. The foam structures are well replicated from the structure of PU foam. No significant defects such as buckling, twisting and rotating of struts were observed. However, a close examination reveals that the strut surface of foams is rougher than the PU foam. This is likely caused from incomplete investment casting with retained plaster and shrinkage after cooling. In the case of pure materials, when no particle was added to foams, the strut surface is clean, as shown in Figs. 2a and 2b.

The presence of SiC particles on the strut surface was observed when the particles were added to foams, as presented in Figs. 2c-2f. A large amount of SiC particles on the strut surface was seen from the foams with 5 wt.% particles. It is clear that more particles present at strut surface when higher particle content was added to foams. The particles also tend to form small clusters when the particle content increases. It should be noted that the strut surface of foams have a small remnant of broken plaster adhered to the surface. Nevertheless, this remnant has much larger size than the SiC particles and thereby can be easily distinguished. It is proved difficult to remove all broken plasters, particularly for fine size, during cleaning process.

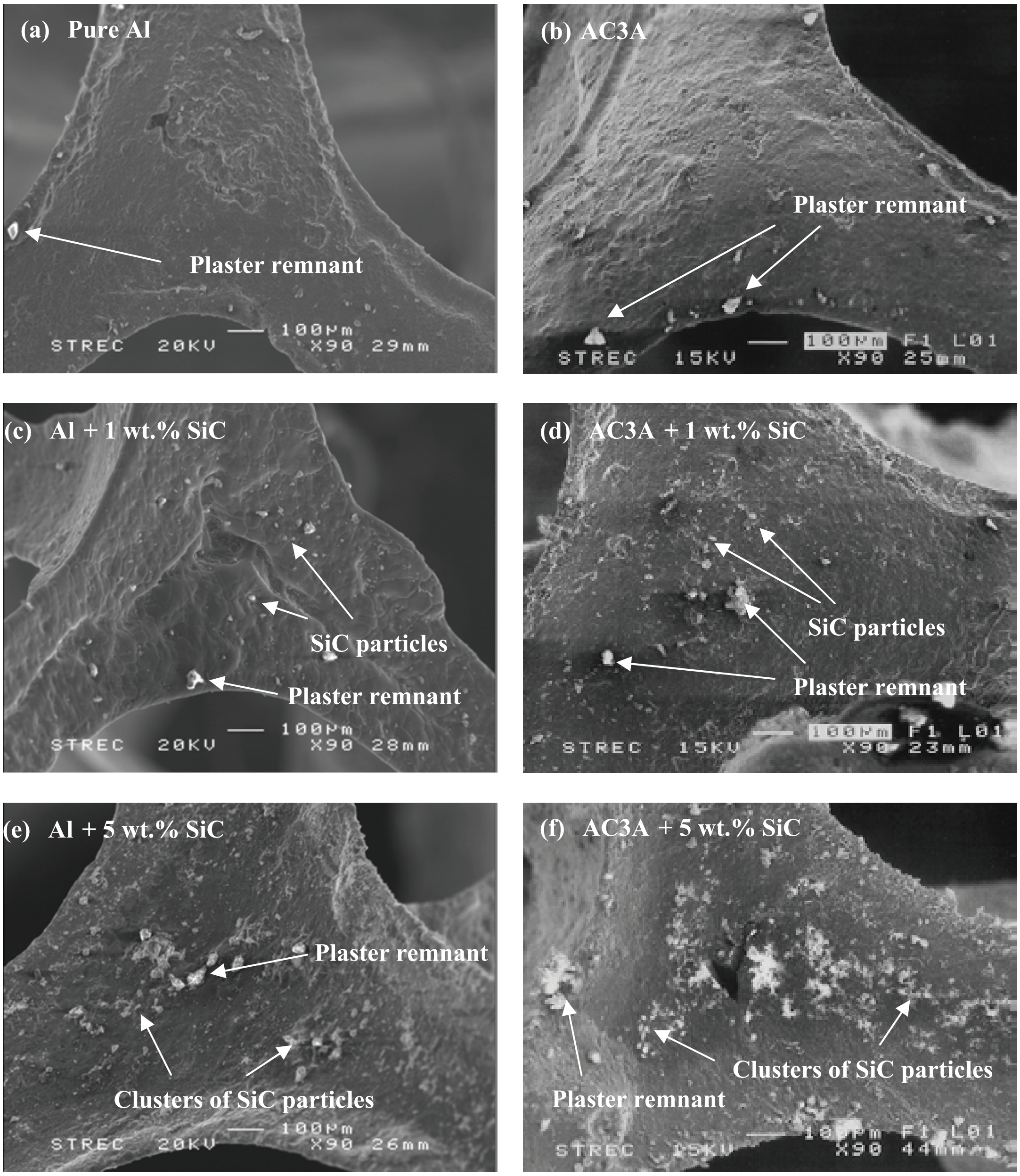

Fig. 2. SEM micrographs showing the macrostructure of Al and AC3A composite foams

Fig. 3 presents the microstructure of Al and AC3A composite foams. It can be seen that the microstructure of both types of foams is different in matrix phase. The dendrite structure with an acicular type of eutectic Si is found in the matrix phase of pure AC3A and AC3A composite foams. Additionally, microvoids are observed in both types of foams. The formation of microvoids is thought to be the effect of metallic shrinkage during solidification coupled with entrapped gas in Al and AC3A melts. The examination of microstructure of composite foams exhibits that SiC particles are embedded in the matrix and distributed throughout foam structure. In all cases, the distribution of particles is rather uniform. No particle agglomeration in the matrix is observed when lower particle content was used. A small clusters of SiC particles are observed in Al composite foam with 5 wt.% particles. However, this is not the case for AC3A composite foam with 5 wt.% particles.

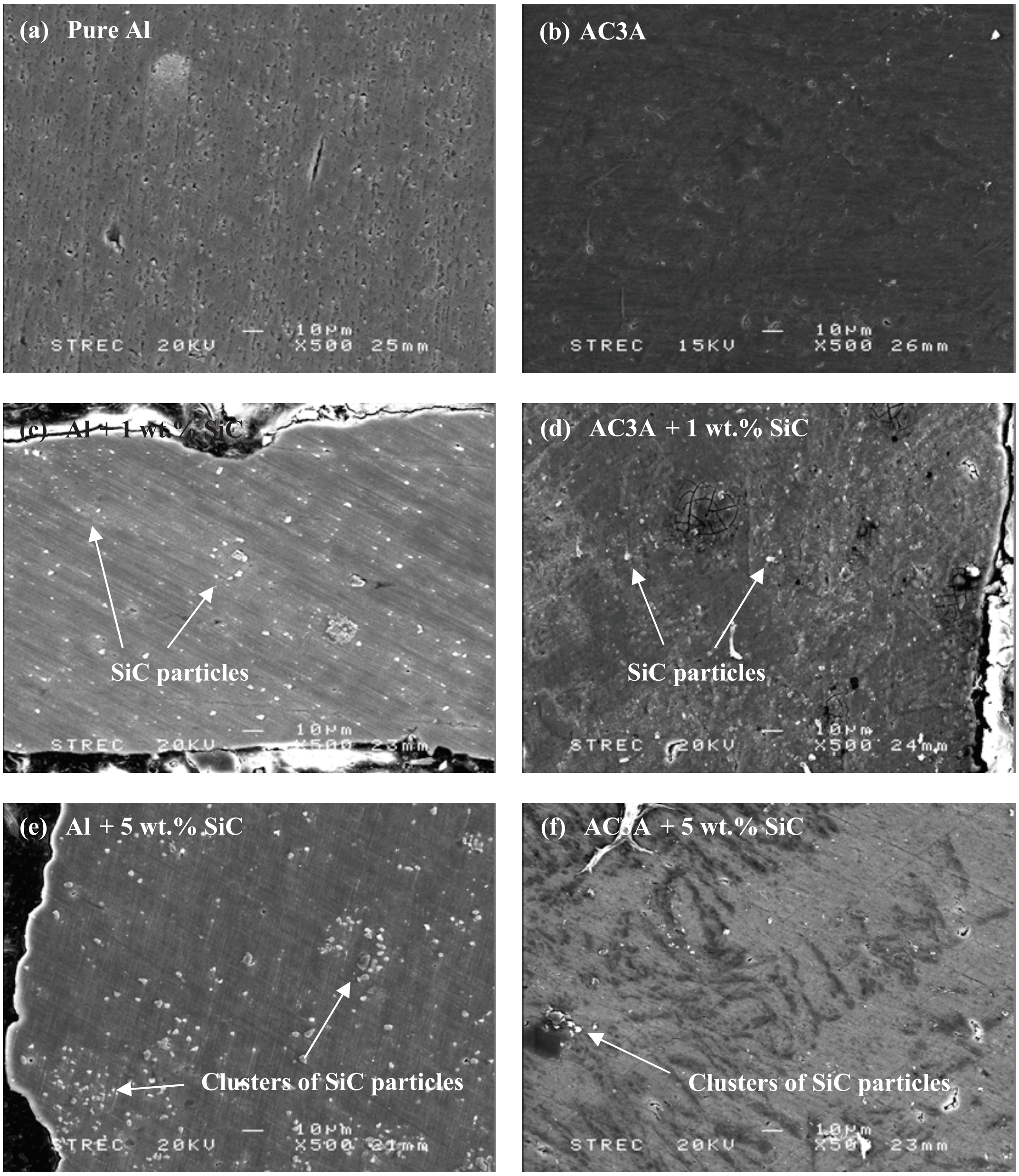

Fig. 3. SEM micrographs showing the microstructure of Al and AC3A composite foams

The compressive mechanical characteristics of Al and AC3A composite foams are shown in Fig. 4. Both types of foams show a typical compressive plot with three distinct regions; elastic, plateau and densification. However, the Al composite foam shows a smooth change in the plateau region of compressive curve, while oscillation in this region is found in the AC3A composite foam. The smooth curve of Al composite foam results from large ductility of pure Al. The brittleness of AC3A composite foam results in fluctuation of stress level. When the brittle foam is compressed, while adjusting the load, cell struts will be collapsed. It is at this point that stress is rapidly decreased. The stress will rise again when no further collapse of struts until local maximum compressive stress is reached. This phenomenon happens in many cycles until all struts collapse.

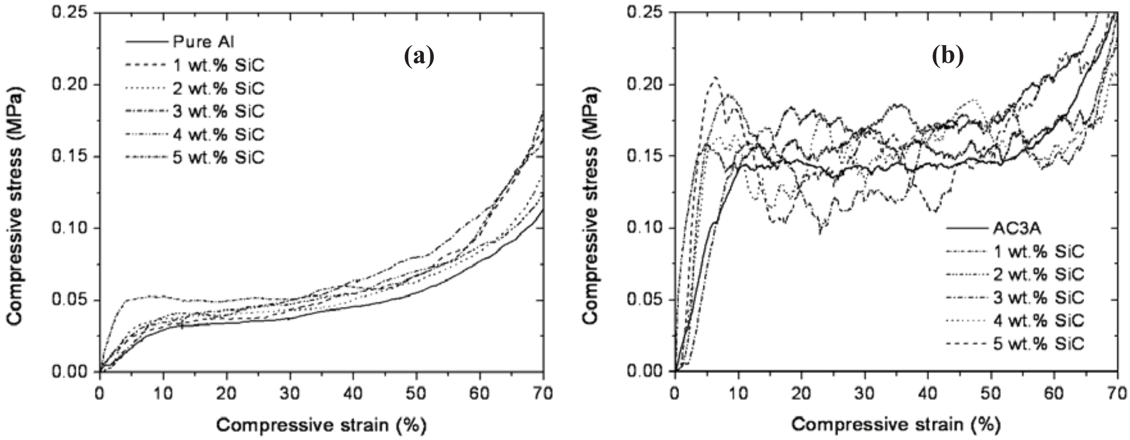

Fig. 4. Compressive behaviors of composite foams: (a) pure Al and (b) AC3A alloy

The yield strength of composite foams, in all cases, increases with increasing SiC particle addition, as shown in Fig. 5. The effect of particle addition is more pronounced in AC3A composite foam than Al composite foam. The yield strength of AC3A composite foam increases more rapidly than the Al composite foam. Moreover, an increase in SiC content in foams results in more stress oscillation, suggesting that brittleness of foam increased.

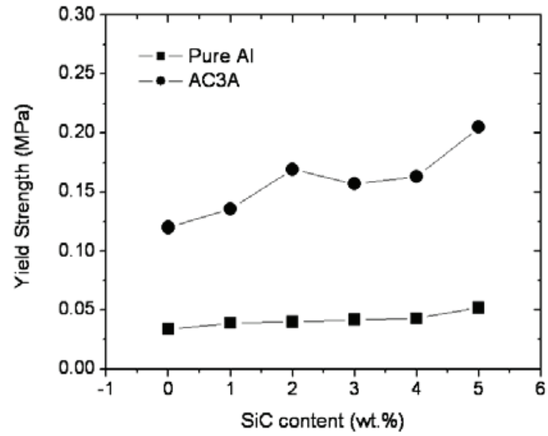

Fig. 5. Yield strength of Al and AC3A composite foams

4. Conclusion

The comparative study of two types of composite foams; Al and AC3A, with various contents of SiC addition was conducted. It is found that the macrostructure of both types of foams is similar, with more presence of SiC particles at strut surface when higher particle content is added to foams. The microstructure of these foams, however, is dissimilar due to the difference in the matrix phase of base metals. A better uniform distribution of SiC particles in the matrix is found in the AC3A composite foam. Although both types of composite foams have similar foam structure and particle content, but the disparity in microstructure resulted in distinct mechanical properties. The AC3A composite foams for all particle contents are brittle and have higher strength than the ductile Al composite foams. An increase in particle content in foams results in an increase in foam strength, and this effect is more pronounced for the AC3A composite foams.

Acknowledgements

The research grant for the present work obtained from the Ratchadaphiseksomphot Endowment Fund of Chulalongkorn University and sample preparation supports from Luna Co., Ltd. are acknowledged.

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